
Neutrino Physics in INDIA

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On Behalf of Indian Institutions

Intensity Frontier Workshop

November 30 – December 2, 2011

Rockville, MD

**FUNDAMENTAL PHYSICS AT THE
INTENSITY FRONTIER**

November 30 - December 2, 2011
Rockville, MD



PLAN OF THE TALK

➤ Neutrino Physics in India

Domestic Program

- ❖ India-based Neutrino Observatory (INO – ICAL) - Talk by Raj Gandhi on “INO Physics & Status” in Session 4 - “Joint Session with Proton Decay WG on Large Detectors” – 1.12.2011

International Collaboration

- ❖ Indo-US Neutrino Collaboration
 - Near Term Plan (2010 -2015)
 - Long Term Plan (2015 and Beyond)

INDO – US NEUTRINO COLLABORATION @ INTENSITY FRONTIER

**Near Term Plan – MIPP-I, MINOS,
MINOS+, NO ν A, LBNE ND**
**Long Term Plan – LBNE with/700 kW
Beam, LBNE w/Project-X**

HISTORY OF INDIAN COLLABORATION AT FERMILAB

1. Emulsion exposure in 200 and 400 GeV beam – late 70's
2. Di-muon (DY) experiment – as individual collaborators – late 70's
3. Fixed target experiment E706 – DU – 1985 - 1992
4. Tevatron Collider D0 – DU, PU, TIFR – since late 80's, early 90's (Students are still working on data analysis and Ph.D thesis)

Visit of US team in 11/2003 to discuss further collaboration:

5. Accelerator Collaboration – RRCAT, IUAC, BARC, VECC, IGCAR ~2006
6. Neutrino Collaboration – Since 2009

Across the board on Fermilab Neutrino Experiments

Working/planning to work on MIPP, MINOS, MINOS+, NOvA, LBNE [pre-Project-X (w/700kW beam power) and with Project-X (~2.3 MW beam)] -

Institutions Involved - BHU, CUSAT, DU, IITG, IITH, JU, HU, PU.

More institutions have expressed interest.

UMBRELLA MOU between INDIAN and US INSTITUTIONS - 2006

Memorandum of Understanding
between
US Universities & Accelerator Laboratories
and
Indian Universities & Accelerator Laboratories
concerning
Collaboration on R&D for Various Accelerator Physics and High
Energy Physics Projects
January 9, 2006

1. Introduction

1.1 General Description

This Memorandum of Understanding (MOU) establishes a collaboration framework between various US and Indian Accelerator Laboratories and Universities, hereinafter referred to as the "Parties", to pursue coordinated R&D in areas of mutual interest pertaining to accelerator and high energy physics projects. This agreement between the Parties is made to further the objectives of any existing national and international collaborations, and shall not alter those collaborations. This MOU between the Parties is not a legal contractual obligation on the part of any of the institutions that are a party to the agreement.

1.2 Objective

The objective of this MOU is to document the terms under which work of the Parties is to be performed.

1.3 Scope

This MOU covers work to be performed by the Parties in the furtherance of the goals of the collaborations and the specific R&D tasks within the topics of collaboration.

1.4 Initial List of Participating Institutions


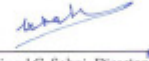
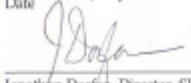


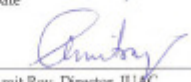
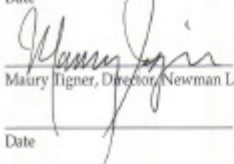
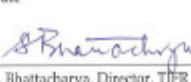
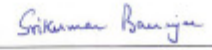

The following is a list of the Institutions that are a party to the collaboration. The Parties agree that after mutual consultation, they would favorably consider admitting new partner institutions from the USA and India who want to contribute towards the objective of this Agreement.

1

01/09/06

4.2 Approvals

The following concur in the terms of this Memorandum of Understanding:

 Piermaria Oddone, Director, FNAL	 Vinod C. Sahni, Director, CAT
Date <u>1/9/05</u>	Date <u>March 8, 2006</u>
 Jonathon Dorfman, Director, SLAC	 Bkash Sinha, Director, VECC
Date <u>1/23/06</u>	Date <u>March 9, 2006</u>
 Christoph Lechner, Director, TJNAJ	 Amit Roy, Director, IUAC
Date <u>1/18/06</u>	Date <u>March 9, 2006</u>
 Maury Tigner, Director, Newman Lab	 S. Bhattacharya, Director, TIFR
Date _____	Date <u>April 17, 2006</u>
_____	 S. Banerjee, Director, BARC
Date _____	Date <u>March 14, 2006</u>
_____	 Deepak Pant, Vice Chancellor, DU
Date _____	Date <u>April 10, 2006</u>

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01/09/06

MOU on v Collaboration between Indian Institutions & FERMILAB - 2009

ADDENDUM
to the
Memorandum of Understanding
between
US Universities & Accelerator Laboratories
and
Indian Universities & Accelerator Laboratories
concerning
Collaboration on R&D for Accelerator Physics and High Energy Physics Projects

Addendum IV: "US and Indian Institutions Collaboration on Neutrino Physics, Related Experiments and Detector Development."

Nov 10, 2009



1. Authority and Limitations

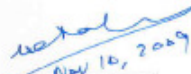

Pursuant to the Memorandum of Understanding ("MOU") between the U.S. Universities & Accelerator Laboratories and Indian Universities & Accelerator Laboratories dated January 9, 2006, Fermilab and Indian Accelerator Laboratories (the "Parties") intend to undertake the work described in this Addendum IV. The Parties acknowledge that their intended work shall be consistent with the terms and conditions of the MOU, the terms and conditions of their respective contracts and programs, and subject to the availability of appropriated funds as provided to them. The Parties further acknowledge and understand that their agreement with and signature to Addendum IV does not create a legal, contractual obligation for either Party nor may form the basis of a claim for reliance thereon. The Parties agree to comport their activities under Addendum IV in conformance with all applicable U.S. and Indian laws and regulations, including those related to export control.

2. Introduction

The work detailed in this document falls within the scope of the MOU cited above. It addresses two key areas of collaboration mentioned in the main MOU. These are: (i) Neutrino Physics; and (ii) Development of Novel and Large Particle Detectors. All terms and conditions under which the work will be carried out are found within the main MOU.

The following concur on the terms of this Memorandum of Understanding Addendum:

	10 Nov, 2009		11/16/09
Dr. Amit Roy	Date	Dr. Piermaria Oddone	Date
Director		Director,	
IUAC		Fermilab	

	Nov 10, 2009		11/12/09
Dr. Vinod Sahni	Date	Dr. Shekhar Mishra,	Date
Collaboration Coordinator		Collaboration Coordinator,	
IUAE, India		Fermilab	

	10 Nov 2009		12 Nov. 09
Prof. Brajesh Choudhary,	Date	Prof. Sanjib Mishra	Date
Technical Project Manager		Technical Project Manager	
University of Delhi, India		University of South Carolina, Columbia	

Collaborating Institutions:

1. Banaras Hindu University, Varanasi
2. Cochin University of Science & Tech., Cochin
3. University of Delhi, Delhi
4. IITG, Guwahati
5. IITH, Hyderabad
6. Jammu University, Jammu-Tawi
7. Hyderabad University, Hyderabad
8. Panjab University, Chandigarh

Continuing to discuss collaboration with other institutions. Many more interested.

STATUS OF THE COLLABORATION

- **Strong support from Universities, DAE and DST management for this collaboration.**
- *Administrative approval given by DAE and DST. Expect money by the end of 2011. Amount requested ~\$2M+.*
- **Collaboration in progress since 2009.**
- **Five students and around 10 faculty currently involved in MIPP, MINOS and LBNE.**
- **In last two years we have done analysis, written scientific documents and presented results on MIPP, MINOS and LBNE.**
- **In near term we plan to involve about 15 faculty members and graduate ~20 students by 2015.**

MORE ON INDO-US COLLABORATION



U.S. DEPARTMENT OF STATE

U.S.-India Science, Technology and Innovation Cooperation
Office of the Spokesperson
Washington, DC
July 19, 2011

Discovery Science: The United States' Department of Energy and India's Department of Atomic Energy signed an Implementing Agreement on Discovery Science that provides the framework for India's participation in the next generation particle accelerator facility at Fermilab.

<http://www.state.gov/r/pa/prs/ps/2011/07/168740.htm>

INTENSITY FRONTIER - WHY INTEREST IN NEUTRINOS?

- ✓ θ_{13} – what's the value?
- ✓ Is there leptonic CP violation?
- ✓ Mass hierarchy - whether “normal ($m_3 > m_2 > m_1$)” or “inverted ($m_2 > m_1 > m_3$)”?
- ✓ θ_{23} - is it maximal?
- ✓ Resolve the degeneracy.
- ✓ Supernova neutrinos. Relic neutrinos from supernovae.
- ✓ Precision measurements; large Δm^2 oscillations (LSND, MiniBooNE); and other searches (NSI, Sterile Neutrinos) – with LBNE ND.

Why participate in LBNE and LBNE-ND?

Inspiration from the DAE/DST management – participate if:

- The program is Physics Rich
 - ✓ Compelling Neutrino Physics
 - ❖ *In long run expect at least 50 Ph.Ds from Indian Institutions*
 - ✓ Physics of Near Detector
 - ❖ Participation by Experimentalists / Engineers
 - ❖ Exploration by theorists due to richness of the program
- Indian contribution should be significant and should have DAE-DST ownership
 - ✓ Design, built, and operate either Magnet+ECal+Muon system, or Magnet+ECal, or Magnet+Muon system
- Contribution should have synergy with interest and expertise in India and with INO program
 - ✓ Expertise exists in magnet design, scintillator (for ECal and/or muon) and RPC (muon) detectors and SiPM (Ecal) readout
 - ✓ Compliments INO physics program

Near Detector Concept and Physics?

1. Use of an “identical small detector” at the near site is insufficient for future LBL experiments. Scaling prohibits having identical detector technology for the ND and FD. What should be the aim of an ideal ND? It should provide:

- ✓ Flux of $\nu_e, \nu_\mu, \bar{\nu}_e, \bar{\nu}_\mu$ at ND and FD as function of E_ν and θ_ν
- ✓ Absolute neutrino energy (E_ν) scale
- ✓ Measurement of neutrino induced $\pi^0, \pi^+, \pi^-, p, K^\pm$ flux in NC and CC interactions in ν -H₂O or ν -LAr - backgrounds to oscillation signal
- ✓ Difference between neutrino and anti-neutrino interactions for both electron and muon flavor
- ✓ The LBNE-ND aims to provide precise constraints on the systematic errors affecting the ν oscillations physics – ultimate calibration of the Far Detector

2. Discovery Potential - Sum-rules, iso-spin physics, searches (sterile neutrinos etc.)

3. A whole bunch of very precise measurement

4. Over 75 different topics/papers/thesis (next-page)

PHYSICS POTENTIAL with HiResMv?

APPENDIX A: Physics Potential of HiResMv

Below we enumerate some physics topics which can be studied with the proposed experiment and can be the subject of PhD theses. The list is not complete. It is intended to illustrate the outstanding physics potential of HiResMv; many more there will be.

About NuMI and Service to LBL

- 1: The energy scale and relative flux of ν_μ flux in NuMI
- 2: The $\overline{\nu}_\mu$ relative to ν_μ as a function of E_ν in NuMI
- 3: Relative abundance of ν_μ and $\overline{\nu}_\mu \rightarrow \nu_\mu$ and $\overline{\nu}_\mu$ in NuMI
- 4: An empirical parametrization of K_L^0 yield in NuMI using the $\overline{\nu}_\mu$ data
- 5: Redundancy check on the MIP π^+ , K^+ , π^- , K^- , and K_L^0 yields in NuMI using the ν_μ , $\overline{\nu}_\mu$, ν_e , and $\overline{\nu}_e$ induced charged current interactions

Neutral-Pion Production in ν -Interactions

- 6: Coherent and single π^0 production in ν -induced neutral current interactions
- 7: Multiplicity and energy distribution π^0 production in neutral current and charged current processes as a function of hadronic energy
- 8: The cross section of π^0 production as a function of X_F and J_T in the ν -CC interactions

Charged-Pion & Kaon and Proton & Neutron Production in ν -Interactions

- 9: Coherent and single π^+ production in ν -induced charged current interactions
- 10: Coherent and single π^- production in $\overline{\nu}$ -induced charged current interactions
- 11: Charged π/K /Proton production in the the neutral current and charged current interactions as a function of hadronic energy
- 12: The cross section of π^+/K^+ /proton production as a function of X_F and J_T in the ν -CC interactions

- 44: Measurement of scaled momentum, rapidity, sphericity and thrust in (anti)neutrino charged current interactions
- 45: Search for rapidity gap in neutrino charged current interactions
- 46: Verification of quark-hadron duality in (anti)neutrino interactions
- 47: Verification of the PCA C hypothesis at low momentum transfer
- 48: Determination of the behavior of $R = \sigma_L/\sigma_T$ at low momentum transfer

Nuclear Effects

- 49: Measurement of nuclear effects on F_2 in (anti)neutrino scattering from ratios of Pb/Fe and C targets
- 50: Measurement of nuclear effects on $x F_3$ in (anti)neutrino scattering from ratios of Pb/Fe and C targets
- 51: Study of (anti)shadowing in neutrino and antineutrino interactions and impact of axial-vector current
- 52: Measurement of axial form-factors for the bound nucleons from quasi-elastic interactions on Pb, Fe and C
- 53: Measurement of hadron multiplicities and kinematics as a function of the atomic number

Semi-Exclusive and Exclusive Processes

- 54: Measurement of charmed hadron production via dilepton ($\mu^+ \mu^-$ and $\mu^+ e^-$) processes
- 55: Determination of the nuclear strange sea using the (anti)neutrino charm production and QCD evolution
- 56: Measurement of J/ψ production in neutral current interactions
- 57: Measurement of K_S^0 , Λ and $\overline{\Lambda}$ production in neutrino CC processes
 - 1 of K_S^0 , Λ and $\overline{\Lambda}$ production in antineutrino CC processes
 - 1 of K_S^0 , Λ and $\overline{\Lambda}$ production in (anti)neutrino NC processes

- 13: Measurement of neutron production via charge-exchange process in the CC and NC interactions
- Neutrino-Electron Scattering

- 14: Measurement of inverse muon decay and absolute normalization of the NuMI flux above $E_\nu > 11$ GeV with $\leq 1\%$ precision
- 15: Search for the lepton violating $\overline{\nu}_\mu - e^-$ CC interaction
- 16: The $\nu_\mu - e^-$ and $\overline{\nu}_\mu - e^-$ neutral current interaction and determination of $\sin^2 \theta_W$
- 17: Measurement of the chiral couplings, g_L and g_R using the $\nu_\mu - e^-$ and $\overline{\nu}_\mu - e^-$ neutral current interactions

ν -Nucleon Neutral Current Scattering

- 18: Measurement of neutral current to charged current ratio, R^N , as a function of hadronic energy in the range $0.25 \leq E_{had} \leq 20$ GeV
- 19: Measurement of neutral current to charged current ratio, R^p and R^n , for $E_{had} \geq 3$ GeV and determination of the electroweak parameters $\sin^2 \theta_W$ and ρ

Non-Scaling Charged and Neutral Current Processes

- 20: Measurement of ν_μ quasi-elastic CC interaction
- 21: Measurement of $\overline{\nu}_\mu$ quasi-elastic CC interaction
- 22: Determination of M_d from the QE cross section and the shape of the kinematic variables (Q^2 , Y_H , etc.)
- 23: Measurement of the axial form-factor of the nucleon from quasi-elastic interactions
- 24: Measurement of ν_μ induced resonance processes
- 25: Measurement of $\overline{\nu}_\mu$ induced resonance processes
- 26: Measurement of nucleon form-factors and structure functions
- 27: Study of the transition between scaling and non-scaling processes
- 28: Constraints on the Fermi-motion of the nucleons using the 2-track topology of neutrino

and neutral current

- 61: Measurement of the Λ and $\overline{\Lambda}$ polarization in neutrino charged current interactions
- 62: Measurement of the Λ and $\overline{\Lambda}$ polarization in antineutrino charged current interactions
- 63: Measurement of the Λ and $\overline{\Lambda}$ polarization in (anti)neutrino neutral current interactions
- 64: Inclusive production of $\rho(770)$, $\rho(940)$ and $\rho(1270)$ mesons in (anti)neutrino charged current interactions
- 65: Measurement of backward going protons and pions in neutrino CC interactions and constraints on nuclear processes
- 66: D^*+ production in neutrino charged current interactions
- 67: Determination of the D^0 , D^{*-} , D_s^0 , D_s^{*-} production fractions in (anti)neutrino interactions
- 68: Production of $K^*(892)^+$ vector mesons and their spin alignment in neutrino interactions

Search for New Physics and Exotic Phenomena

- 69: Search for heavy neutrinos using electronic, muonic and hadronic decays
- 70: Search for eV (pseudo)scalar penetrating particles
- 71: Search for the exotic Theta+ resonance in the neutrino charged current interactions
- 72: Search for heavy neutrinos mixing with tau neutrino
- 73: Search for an anomalous gauge boson in pB decays at the 120 GeV p-NuMI target
- 74: Search for anomaly mediated neutrino induced photons
- 75: Search for the magnetic moment of neutrinos
- 76: A test of $q_s - q_d$ universality down to 10^{-4} level
- 77: A test of $q_s - q_d$ coupling down to 10^{-2} level

quasi-elastic interactions

- 29: Coherent ρ^0 production in ν -induced charged current interactions
- 30: Neutral Current elastic scattering on proton $\nu(\overline{\nu}_\mu)p \rightarrow \nu(\overline{\nu}_\mu)p$
- 31: Measurement of the strange quark contribution to the nucleon spin ΔS
- 32: Determination of the weak mixing angle from NC elastic scattering off protons

Inclusive Charged Current Processes

- 33: Measurement of the inclusive ν_μ charged current cross-section in the range $0.5 \leq E_\nu \leq 40$ GeV
- 34: Measurement of the inclusive $\overline{\nu}_\mu$ charged current cross-section in the range $0.5 \leq E_\nu \leq 40$ GeV
- 35: Measurement of the inclusive ν_e and $\overline{\nu}_e$ charged current cross-section in the range $0.5 \leq E_\nu \leq 40$ GeV
- 36: Measurement of the differential ν_μ charged current cross-section as a function of x_H , y_H and E_ν
- 37: Measurement of the differential $\overline{\nu}_\mu$ charged current cross-section as a function of x_H , y_H and E_ν
- 38: Determination of $x F_2$ and F_3 structure functions in ν_μ charged current interactions and the QCD evolution
- 39: Determination of $x F_2$ and F_3 structure functions in $\overline{\nu}_\mu$ charged current interactions and the QCD evolution
- 40: Measurement of the longitudinal structure function, $F_{L,1}$, in ν_μ and $\overline{\nu}_\mu$ charged current interactions and test of QCD
- 41: Determination of the gluon structure function, bound state and higher twist effects
- 42: Precise tests of sum-rules in QPM/QCD
- 43: Measurement of ν_μ and $\overline{\nu}_\mu$ charged current differential cross-section at large- x_H and $-y_H$

77 HiResMnu Topics listed

Many topics are pertinent to oscillation physics

Some non-oscillation topics might lead to discovery

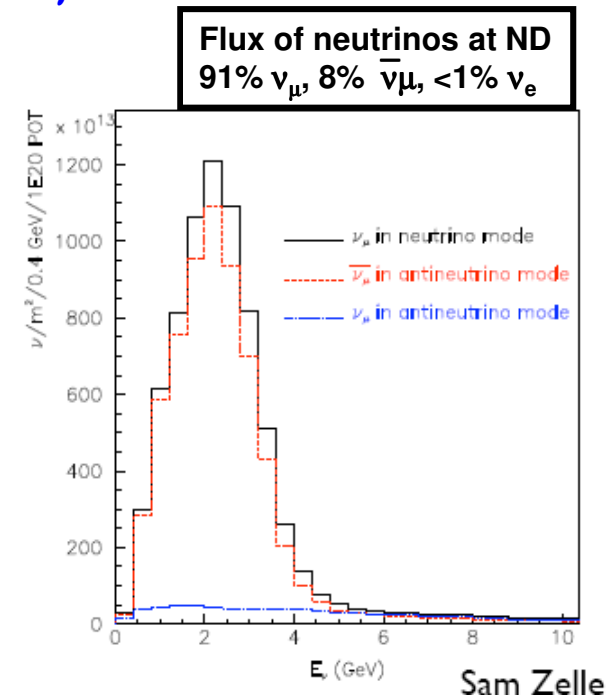
Topics mentioned will have the the highest sensitivity/precision to date

LBNE NEAR DETECTOR REQUIREMENTS

- ✓ Define the measurement required at the near site to meet the goals of LBL neutrino analyses
- ✓ How well we must measure the predicted neutrino fluxes?
 - ✓ *Intrinsic ν_e contamination in the beam*
- ✓ How well we must predict signal and background rates and topologies
 - ✓ *What measurement must be made to accomplish these predictions?*
 - ✓ *Charged current background and signal – extracting the neutrino flux at far site – un-oscillated ν_μ spectrum*
 - ✓ *Neutral current background - ν_μ NC π^0 and NC γ*
- ✓ Both for ν and $\bar{\nu}$ beam
- ✓ Same nuclear target as far detector

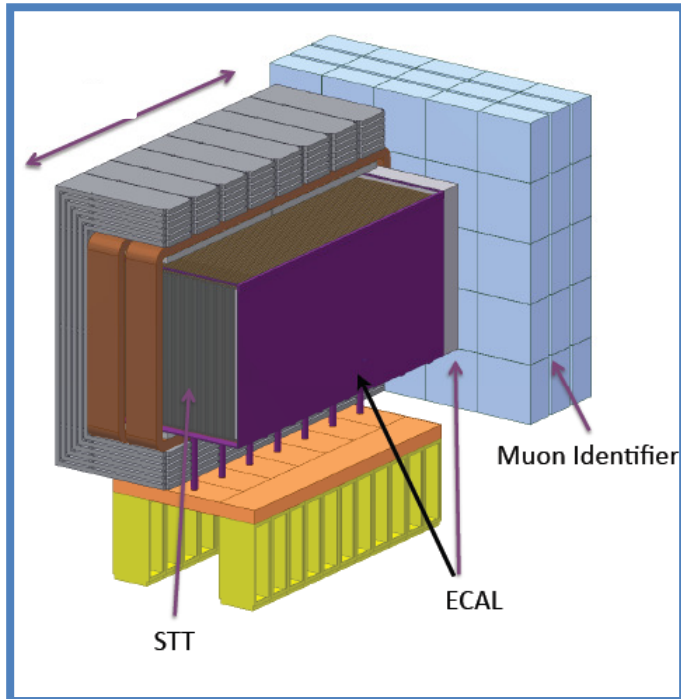
Events per ton per 10²⁰ POT

Production mode	H ₂ O	Ar	Ar/H ₂ O ratio
CC QE ($\nu_\mu n \rightarrow \mu^- p$)	18,977	23,152	1.22
NC elastic ($\nu_\mu N \rightarrow \nu_\mu N$)	7,094	7,165	1.01
CC resonant π^+ ($\nu_\mu n \rightarrow \mu^- N \pi^+$)	25,821	24,014	0.93
CC resonant π^0 ($\nu_\mu n \rightarrow \mu^- p \pi^0$)	6,308	7,696	1.22
NC resonant π^0 ($\nu_\mu N \rightarrow \nu_\mu N \pi^0$)	6,261	6,198	0.99
NC resonant π^+ ($\nu_\mu p \rightarrow \nu_\mu n \pi^+$)	2,694	2,182	0.81
NC resonant π^- ($\nu_\mu n \rightarrow \nu_\mu p \pi^-$)	2,325	2,930	1.26
CC DIS ($\nu_\mu N \rightarrow \mu^- X, W > 2$)	29,989	31,788	1.06
NC DIS ($\nu_\mu N \rightarrow \nu_\mu X, W > 2$)	10,183	10,285	1.01
CC coherent π^+ ($\nu_\mu A \rightarrow \mu^- A \pi^+$)	1,505	1,505	1.01
NC coherent π^0 ($\nu_\mu A \rightarrow \nu_\mu A \pi^0$)	790	790	1.01
NC resonant radiative decay ($N^* \rightarrow N \gamma$)	41		
Inverse Muon Decay ($\nu_\mu e \rightarrow \mu^- \nu_e$)	6	6	1.00
$\nu_\mu e^- \rightarrow \nu_\mu e^-$	11	11	1.00
Other	17,023	17,193	1.01
Total CC	94,948	100,645	1.06
Total NC+CC	129,028	134,189	1.04



Near Detector Concept for LBNE

STRAW TUBE TRACKER (STT) – Current Design



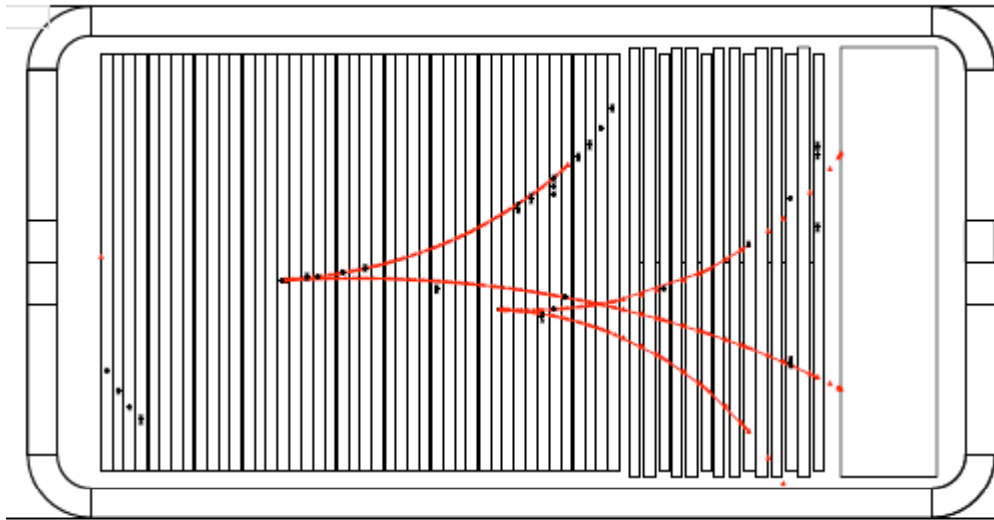
- 2.5m X 2.5m X 4m ($\rho \sim 0.1 \text{ gm/cm}^3$)
- 4π ECAL
- Dipole Field (0.4T)
- Muon-detection (RPC) in Dipole and downstream
- ✓ Transition radiation – distinguished e^\pm , and γ thus distinguishing ν_e , $\bar{\nu}_e$, and π^0
- ✓ dE/dX – separates p , π^\pm , K^\pm
- ✓ Muon + Magnet - μ^\pm
- ✓ H_2O (D_2O) Target ($\sim \text{X5 FD stat.}$) \rightarrow WC-FD
- ✓ QE-Proton ID \rightarrow Absolute Flux measurement
- ✓ Pressurized Ar-Target ($\sim \text{X5 FD stat.}$) \rightarrow LAr-FD

Greatest Scientific Return.

With Indian contribution, it would be possible to build a ***higher-resolution*** and ***larger-ND*** (4m X 4m X 7m) capable of fulfilling oscillation needs and precision measurements/searches.

PI-ZERO (π^0) PRODUCTION IN STT

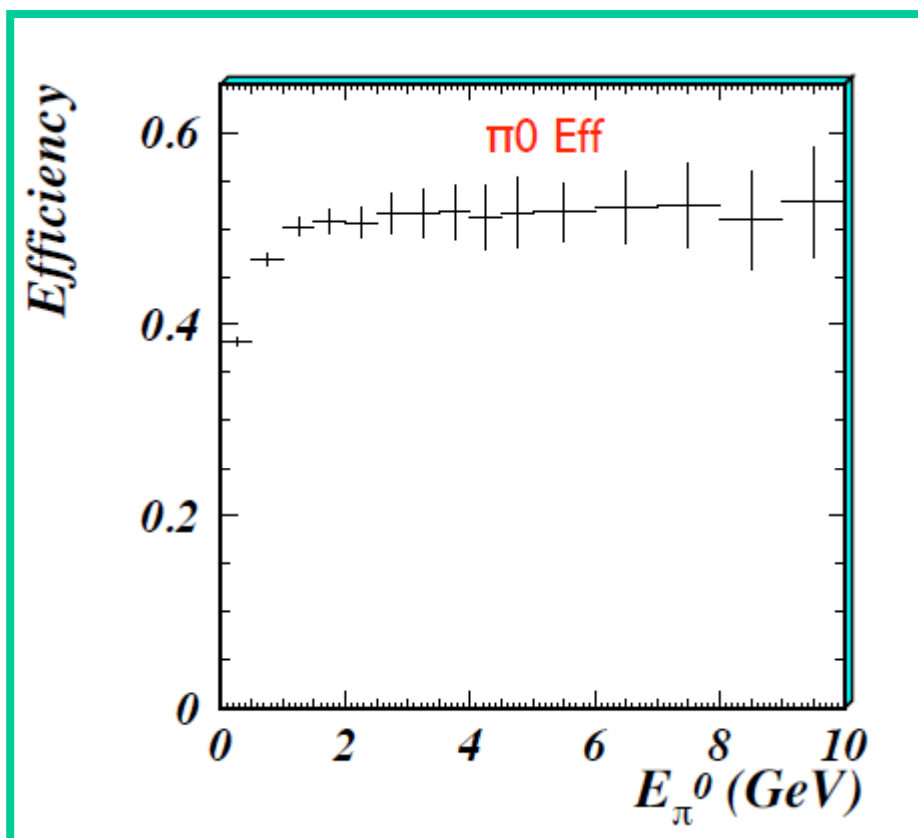
NOMAD DATA



NOMAD DATA
 $\pi^0 \rightarrow \gamma\gamma \rightarrow e^\pm e^\pm$ is
clearly visible

- ✓ In the original version the STT will have 12 times more hits. One can reconstruct e^\pm , γ , and thus π^0 .
- ✓ Measurement of π^0 in NC and CC via $\gamma\gamma$ in tracker. π^0 is the largest background to $\bar{\nu}_e$ appearance.
- ✓ Measure beam ν_e and $\bar{\nu}_e$. A must if there are large Δm^2 ($\sim 1 \text{ eV}^2$) oscillation a la LSND or MiniBooNE.
- ✓ Measure absolute flux.

Why ECAL is critical for LBNE ND?



- ✓ Clean π^0 and γ -signature in STT.
- ✓ ν -NC and CC $\rightarrow \pi^0 \rightarrow \gamma\gamma$. 50% of the γ will convert into e^\pm in the STT, away from the primary vertex. We focus on these.
- ✓ γ -identification. e^\pm ID: TR – using kinematic cut: Mass, opening angle.
- ✓ At least one converted γ in STT. Another γ in the downstream or side ECAL.

Conclusion $\rightarrow \pi^0$ is very well constrained in CC and NC.

WHY a B-Field?

1. Constrain E_ν flux.
2. ND must measure the full range of E_ν and θ_ν else the sensitivity of FD will be compromised.
3. For LBNE, the maximal sensitivity for δ_{CP} is at $E_\nu = 1.5$ GeV.
4. STT will be able to distinguish μ^+ and μ^- down to 0.3 GeV.

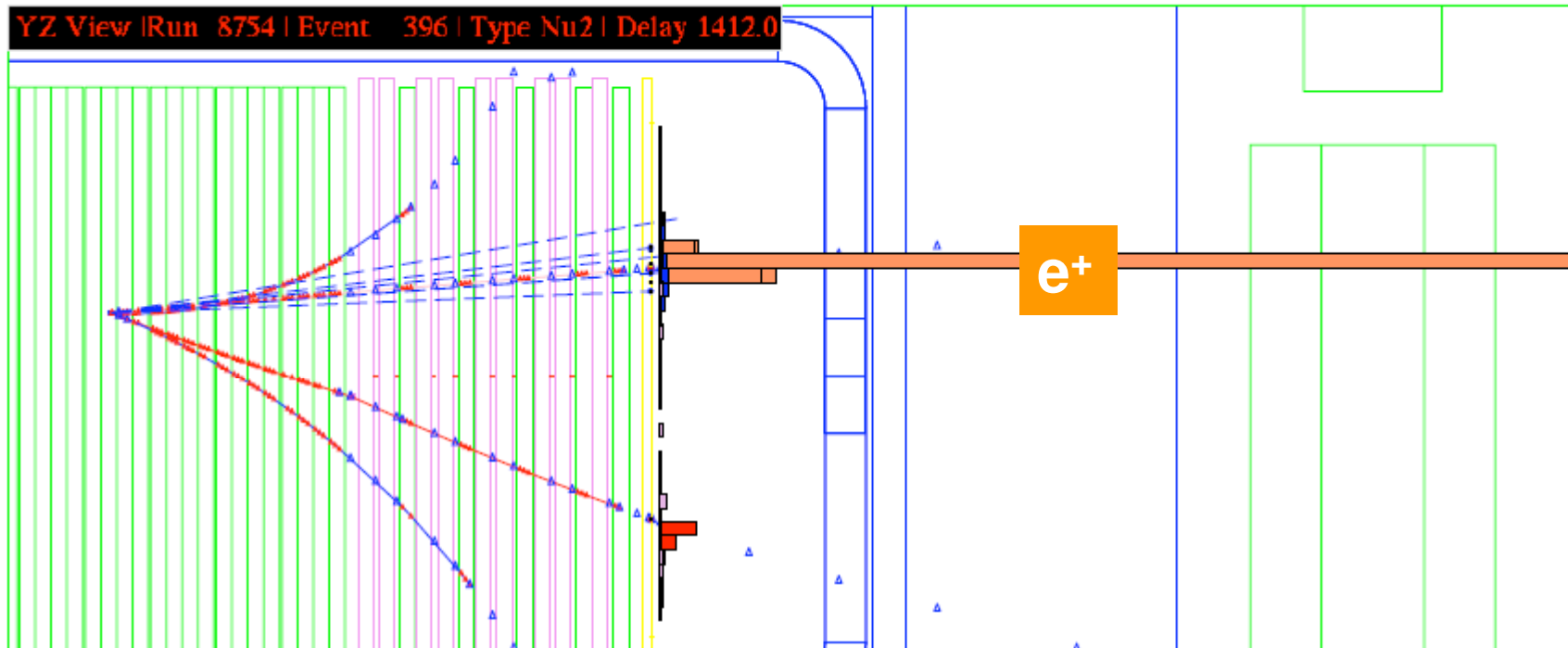
Also the ND must measure and identify leptons (both muons and electrons) at large angles.

Must measure the difference in ν_e and $\bar{\nu}_e$ interactions which might fake a “ δ_{CP} ” in the range 0.5-1.0 GeV

SUMMARY – ND must have a magnetic field.

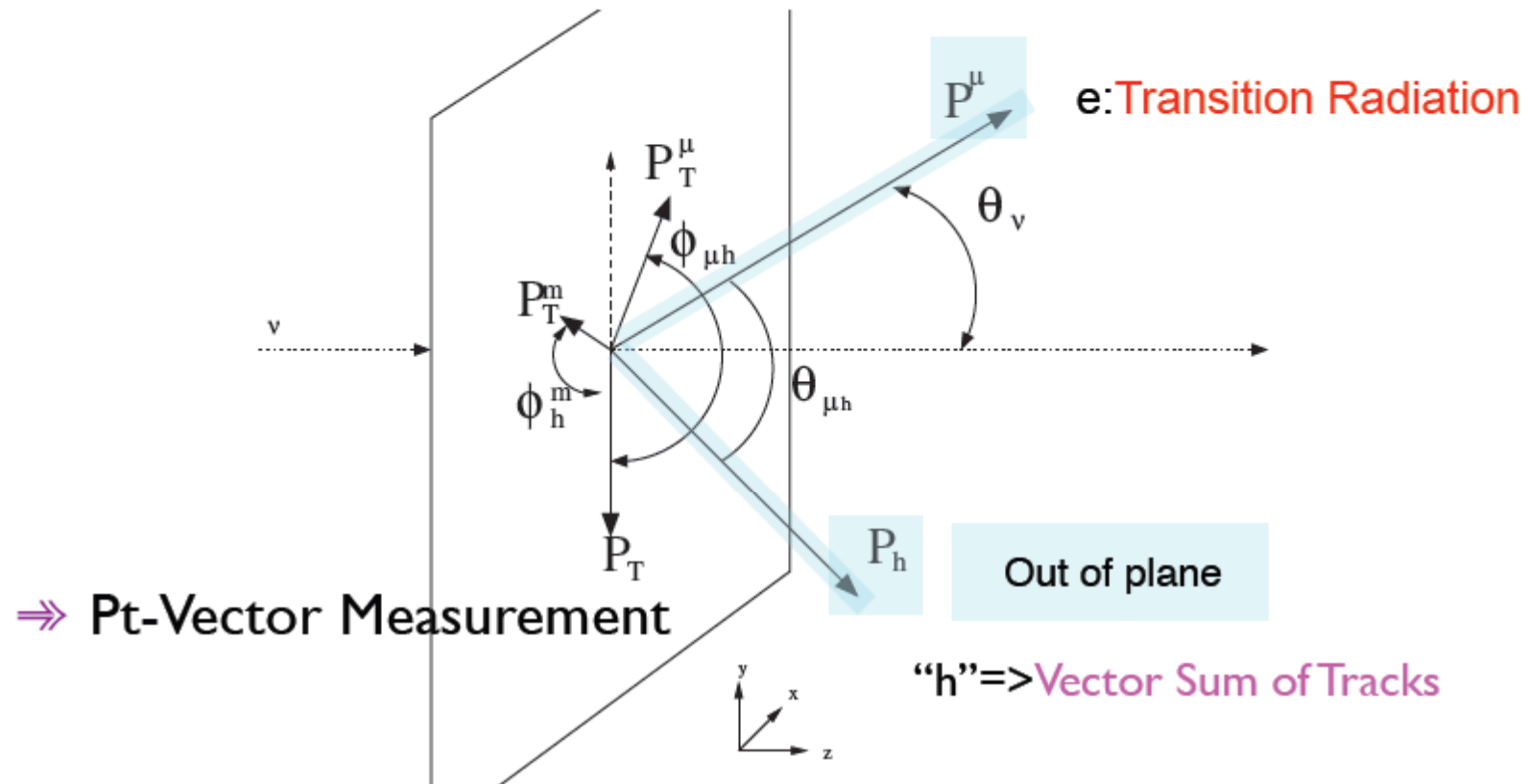
ν_e and $\bar{\nu}_e$ CC MEASUREMENT

The most difficult of neutrino species to identify



- ✓ X12 higher sampling in STT.
- ✓ X 4π calorimetric and μ coverage.
- ✓ ECAL is critical for ν_e , $\bar{\nu}_e$, and π^0 reconstruction.
- ✓ $\bar{\nu}_e$ most difficult to reconstruct in any neutrino experiment.
Only $\sim 0.2\%$ of ν_μ CC events.

KINEMATICS IN STT DETECTOR



1. Allows to reconstruct P_t^μ and P_h in a plane \perp to the neutrino direction. Neutrino is parallel to the detector.
2. Implies event wise measurement of missing P_t vector - E_ν scale.
3. In ideal CC case it will be zero. For NC case – large missing P_t .
4. Allows to classify and understand the event. Only STT can do it.

PROTON IDENTIFICATION

1. Precision determination of ν_μ - QE requires proton tracking.
2. Example of a ν -interaction in a high resolution ND as a calibration of FD. Need proton-tracking & resolution to point to the H_2O and D_2O vertex.
3. QE in H_2O and D_2O will provide an absolute-flux measurement.
4. μ^-, p provide an “*in situ*” constraint on the Fermi-motion and hence on the E_ν scale.
5. QE interactions dominant in low- E_ν . Need accurate parameterization of QE.
6. So – ND must track and ID QE-protons.

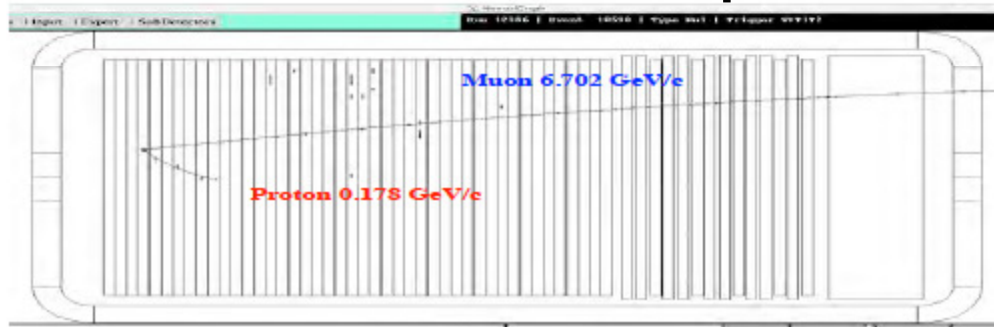


Figure 14: A ν_μ -QE candidate in NOMAD

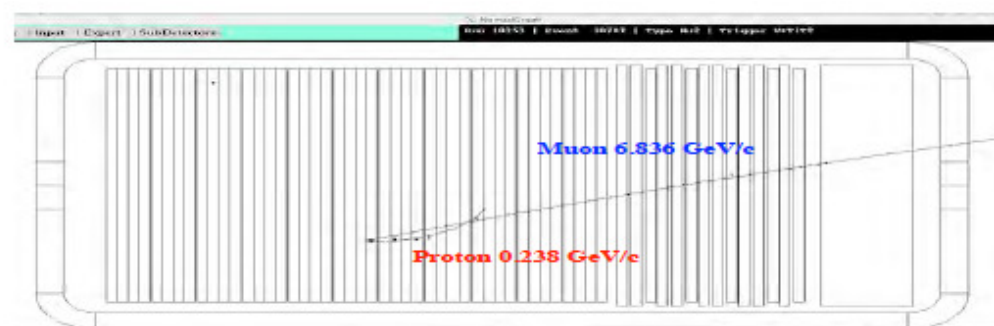


Figure 15: A ν_μ -QE candidate in NOMAD

Use NOMAD data/MC as calibration.

In the original version, the STT will have X6 more points for protons.

Such low proton momentum quite common at LBNE.

Measurement of the RATIO $\mathcal{R}_{e\mu}$?

- ❖ Search/Impact of large Δm^2 oscillations. If these exists then the assumption that flux at ND is unoscillated is false.
- ❖ Independent analysis of ν -data and $\bar{\nu}$ -data due to possible differences between MiniBooNE/LSND results.
 - ✓ Need a detector which can identify e^+ and e^- .
- ❖ Measure the ratio between the observed ν_e ($\bar{\nu}_e$) CC events and the observed ν_μ ($\bar{\nu}_\mu$) CC events as a function of L/E_ν :

$$\mathcal{R}_{e\mu}(L/(E\nu)) \equiv \frac{\# \text{ of } \nu_e N \rightarrow e^- X}{\# \text{ of } \nu_\mu N \rightarrow \mu^- X} (L/(E\nu))$$

$$\bar{\mathcal{R}}_{e\mu}(L/(E\nu)) \equiv \frac{\# \text{ of } \bar{\nu}_e N \rightarrow e^+ X}{\# \text{ of } \bar{\nu}_\mu N \rightarrow \mu^+ X} (L/(E\nu))$$

- ❖ Compare the measured ratios $\mathcal{R}_{e\mu}(L/E_\nu)$ and $\bar{\mathcal{R}}_{e\mu}(L/E_\nu)$ with the predictions from the ν -flux determination assuming no oscillations
- ❖ Same analysis technique used in NOMAD to search for $\nu_\mu \rightarrow \nu_e$ oscillations
- ❖ MiniBooNE effect is at 1% level. LSND measurement at 0.1% level.

INDIAN INTEREST IN LBNE – ND (STT)

1. A fine-grained ND is important for achieving LBNE aims.
2. Having a segmented ND helps in participation.
3. The Indian participants have proposed to Indian funding agencies (DAE and DST) to build a significant part of the STT-ND. Our ambition is to built:
 - ✓ Dipole Magnet - Fabrication through Indian Industry
 - ✓ ECAL - Scintillator Detector + SiPM (a la CMS)
 - ✓ Muon-Detector (RPC a la INO)
4. Total Cost = \$50M (Rs. 250 crores)
5. *Fulfills DAE-DST requirements of*
 - *Rich Physics*
 - *Significant contribution with DAE-DST Ownership*
 - *Synergy/Interest*

Summary and Conclusions

- **The Indo-US neutrino collaboration is progressing well.**
- **We aim to further expand this collaboration towards a compelling neutrino program at the intensity frontier.**
- **Propose to make a significant contribution to LBNE, with 700kW and beyond, with a clear DAE-DST flag.**
- **Will train and generate manpower towards future scientific projects in India.**
- **Complementary and synergistic to our indigenous efforts.**
- **Indian industry can play major role in detector fabrication.**

Summary and Conclusions

- To make a significant and clearly visible contribution to LBNE, we have asked the Indian funding agencies for a leadership level contribution to the Near Detector.
- An encouraging statement from the US funding agencies on the time frame of the LBNE experiment and Project-X will be important in securing support from Indian funding agencies.

THANK YOU